INNOVATION IN THE DESIGN OF CROSS LAMINATED TIMBER FOR LONG SPAN FLOORS

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ABSTRACT

Cross Laminated Timber (CLT) construction is now considered a viable and sustainable alternative to traditional building techniques within the multi-storey building sector. This is primarily due to the high level of prefabrication possible with CLT construction, its high strength-to-weight ratio and its potential as a carbon negative building material. As a result, an increasing number of developers and architects are requesting a CLT design option for multi-storey buildings using CLT wall and floor panels. The latter, especially long span floors, provides a challenge for engineers. Long span CLT floors have a lower natural frequency and are light in weight, which can cause noticeable vibrations. This paper examines existing analytical design procedures available to calculate floor vibrations and provides a preliminary design for floors spanning 9 m. Innovations in CLT panels are introduced, including increased connection rigidity and the use of hardwood timber species, resulting in increased panel stiffness and reduced floor vibrations. Whilst CLT has been extensively researched and tested in Europe and Canada, only limited research has occurred within Australia and New Zealand. This paper also discusses Australian and New Zealand standards and codes and the use of locally grown soft and hardwood timber species for CLT panels.

KEYWORDS

Cross Laminated Timber, Sustainable Materials, Floor Dynamics, Long Span Floors, Structural Design

INTRODUCTION

Vibration design has become an important design parameter for timber floors due to the increasing demand for longer spans and lighter structures for commercial buildings. For timber floors over 4 m, the floor design is generally governed by ensuring acceptable levels of vibration (Thiel 2013). Current market trends indicate the need for timber floor solutions to satisfy a 9 x 9 m floor grid to ensure competitiveness with concrete and steel construction. The criteria of a 9 m spanning floor allows for open plan office spaces and efficient parking arrangements between columns required by commercial buildings.

Cross laminated timber (CLT) is a slab like engineered wood product composed of a number of panels of sawn lumber glued and pressed together, with each layer orientated orthogonal to the adjacent layer (Figure 1). The multi-storey timber building market is currently expanding, with several existing examples of CLT buildings up to 12 storeys and more currently in the planning process (Brandner 2013). To span a 9 m floor with CLT panels is challenging as the product will lose its edge over traditional concrete slab design if the weight or thickness of the panel required to satisfy vibration design becomes too large. Accurate vibration design and specifications are therefore essential for ensuring an optimised floor layout.

Vibration design guidelines from Australian standards and codes are currently limited. AS1170.0 (2002) provides a static unit deflection limit, requiring the deflection of a floor under a mid-span unit point load of a maximum 1-2 mm. Specifically, in the timber design standard AS 1720.1 (2010) attention is drawn to the fact that “deflection limits do not necessarily ensure satisfactory dynamic performance”, however no other guidelines are given. Reference is made to AS 2670 (2001) which provides acceptability limits in the form of root mean square (RMS) accelerations, however this does not provide analytical equations for the vibration design of the floor layout.

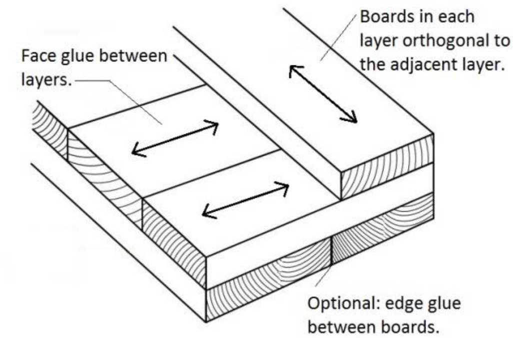

Figure 1 Layout of cross laminated timber.

A number of analytical methods for modelling vibrations have been developed and expanded in both Europe and Canada. These methods provide calculations and limits for natural frequency, unit deflection, velocity and acceleration of CLT floors. The limit for frequency is based on avoiding resonance with walking (around 3Hz) and a comprehensive study of more than 100 problematic floors that were found to have a frequency range of 5-8 Hz (Murray et al. 1997). Eurocode 5 provides calculations that allow a minimum natural frequency of 8 Hz. However, further studies by Hamm et al, (2010), on floors of 50 existing buildings found some floors with natural frequencies over 8 Hz, particularly the lighter floors, did not satisfy acceptable vibrations while a number of floors with natural frequencies between 5-8 Hz had acceptable vibration performance. The study found that the stiffness and the acceleration of the floor were also important parameters and provided an extension to the Eurocode 5 method that allowed floor natural frequencies below 8 Hz.

Parameters that affect the vibration performance of a floor include stiffness, damping and mass as well as the support rigidity and any two-way action from CLT that can be utilised (Weckendorf et al. 2008). This paper investigates the effect of varying stiffness, support conditions and two-way action, on the preliminary design of a cross laminated timber floor spanning 9 m. This paper also provides a comparison of the analytical methods that have been developed for calculating the vibration performance of a timber floor and demonstrates that these methods provide vastly different design solutions due to the subjective nature of the design limits.

Finally the paper considers material properties satisfying F-grades in accordance with AS1720.1 (2010), since both structural and non-structural Australian *Pinus Radiata* have shown promise for use as CLT panels (Sigrist & Lehmann 2014).

FLOOR PROPERTIES

The preliminary design for the 9 m panel was sized to satisfy strength and both short and long term deflections. Two panels were chosen for preliminary analysis: an 8 layer CLT panel (Floor 1) with a high stiffness in the longitudinal direction and a 7 layer CLT panel (Floor 2) with a lower stiffness longitudinally but with a higher transverse stiffness (Figure 2). Material was kept constant between the two; using F11 graded seasoned softwood timber with a density of 550 kg/m^3, similar to grades of commercially available CLT panels.

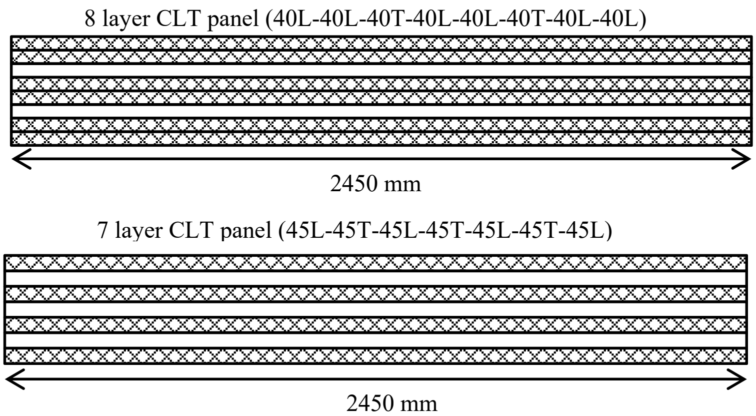

Figure 2 Cross sections of CLT panels for preliminary design. Top: Floor 1, 8 layered CLT panel, 320 mm thick. Bottom: Floor 2, 7 layered CLT panel, 335 mm thick.

There are a number of methods for calculating the effective section modulus, EI_{eff}, of a cross laminated timber panel. These have been developed based on mechanically jointed beam theory to take into account the decrease in stiffness due to the shear slip caused by the transverse layers. The CLT Handbook by FPInnovations provides a comprehensive outline, including worked examples of these methods (Gagnon & Popovski 2011). This study considers the Gamma method as outlined by Eurocode 5, however, all the methods provide accuracy of effective stiffness for ratios of span/depth over 15 (Thiel & Schickhofer 2010).

Since the floor is to comply with Australian Standards for commercial flooring, the live load was taken as Q = 3kPa while a superimposed dead load for finishes and services was considered as G_{SI} = 1.5 kPa. According to AS1720.1, a creep factor of j_2 = 2 is used for long term deflections of plywood. Due to the orthogonal arrangement of CLT similar to that of plywood, the panels are prone to time dependent deformations under load, more than other unidirectional products and hence the values have been found to be comparable (Pirvu & Karacabeyli 2014).

The effective stiffness, EI_{eff} of Floor 1 was found to be 59.1 x 10^{12} Nmm^2 while the effective stiffness of Floor 2 was found to be 56.8 x 10^{12} Nmm^2. The values calculated for design bending moment and deflections, including the limits used, are displayed in Table 1. The long term deflection governed the preliminary design of the floor with 87% and 92% acceptability rates for Floor 1 and Floor 2, respectively.

Table 1 The design of CLT panels satisfying strength and deflection limits according to ULS and SLS design.

	Floor 1			Floor 2		
	Design Value	Design Limit	Acceptability	Design Value	Design Limit	Acceptability
Bending Moment (kNm)	1026	208	20%	934	210	22.5%
Deflection Short term G+0.7Q (mm)	18.9	30 (Span/ 300)	63%	19.9	30 (Span/ 300)	66%
Deflection Long term G+0.4Q (mm)	31.4	36 (Span/250)	87%	33.2	36 (Span/250)	92%

ANALYTICAL METHODS

The analytical methods that have been developed to calculate the vibration performance of a CLT floor assess one or more of the following properties; stiffness, natural frequency, velocity and acceleration of the floor. The methods compared in this paper are methods from Eurocode 5 (2008), modifications of Hamm et al. (2010), modification by Mohr (1999) and the CLT Handbook criteria (Hu & Gagnon 2011). These methods and the criteria they use to assess the floor, including limit values are summarised in Table 2.

Table 2 Comparison of available analytical models for determining vibration performance.

	Stiffness (Unit Displacement)		Floor Natural Frequency		Floor Velocity		Acceleration (floors under 8 Hz only)	
Vibration Performance Method	Load kN	Limit mm	Load Case	Limit Hz	Velocity	Limit	Frequency Range Hz	Limit m/s^2
Eurocode 5	1	≤1	G_{TOT}	≥8	(5	(4		
Hamm et al	2	≤0.5	G_{TOT}	≥8			4.5 - 8	≤0.05
Mohr	1	≤1	G_{TOT}+0.3Q	≥8	(9	(9	3.4 - 8	≤0.1
CLT Handbook	1	*	G_{TOT}	*				

*CLT Handbook criteria the floor frequency is dependent on the floor stiffness and vice versus.

The methods from European research and standards (Eurocode 5, Hamm et al. and Mohr) require one to first define the vibration requirements of the floor; normal or high. High requirements are considered for commercial buildings and multi-storey residential blocks, whereas normal requirements are considered for single unit dwellings. Since this research is concerned with long span floors, primarily found in commercial buildings, high requirements for vibration are considered.

CLT is a plate type timber product rather than a linear beam element and therefore this paper considers a 1 m cross section of the panel to determine the effective stiffness ($EI_{eff,1m}$) rather than the entire width of the CLT panel. For calculating the cross sectional stiffness, the methods discussed generally consider only the boards in the longitudinal direction and discount the transverse boards. In doing so, the reduction in cross sectional stiffness due to the shear slip of the transverse boards is not considered. To date, there has been no agreed upon method for calculating the value of EI, this paper considers both the effective stiffnesss (EI_{eff}) and the longitudinal stiffness (EI_l), depending on the recommendations from the method under consideration.

Eurocode 5

Eurocode 5 provides guidelines for providing acceptable vibration design of residential timber floors. For these calculations, both the longitudinal stiffness (EI_l) and stiffness transverse to the span (EI_t), for a 1 m wide cross section of CLT are used to calculate the natural frequency, deflection limit and floor velocity.

The natural frequency of the timber floor, calculated using (1, is limited to a minimum of 8 Hz, to avoid vibrations caused by resonance. Eurocode states that frequencies of 8 Hz can be acceptable with a "special investigation" required, however, it does not provide guidelines for this investigation (CEN 2008). The factor for support stiffness (k_m) in Eurocode 5 is equal to π^2 which represents a single span simply supported floor. For a fully fixed single span floor the stiffness factor is equal to 22.4 (Thiel 2013).

$$f_1 = \frac{k_m}{2\pi l^2}\sqrt{\frac{(EI)_l}{m}} \geq 8\,Hz \tag{1}$$

The mass, m, is treated as a static mass; equal to the self-weight of the floor plus any extra super imposed weight. Further to checking natural frequency, the deflection due to a unit force ((2) is limited to a maximum value a, which is dependent on the required vibration performance level of the floor. A graph is provided in the code that displays the relationship between the limit value for deflection, a, and the limit value for velocity, b (Figure 3). The calculations are based on a rectangular floor supported on all four sides. Therefore an equivalent beam width, b_{eff}, is calculated to determine the panel's equivalent beam effective stiffness, EI_b, taking into account the transverse stiffness using (3 (Mohr 1999). Since this paper considers floors with higher requirements for vibration, the limit values are taken as a = 1 mm/kN and b = 120.

$$w_{EC5} = \frac{1}{48}\frac{Fl^3}{EI_b} \leq a\,mm/kN \tag{2}$$

$$b_{eff} = \frac{l}{1.1}\sqrt[4]{\frac{EI_t}{EI_l}} \tag{3}$$

The velocity (v) due to an impulse of 1Ns is then calculated using (5 and limited by (4. Only the number of first order modes with natural frequencies up to 40 Hz is considered and calculated using (6. A value for damping, ζ = 1%, is provided by the code. Research has found that for light weight timber floors the first mode of vibration of damping is generally around 2%, however when considering higher modes, the damping can be as low as 0.8% (Weckendorf et al. 2008).

$$v \leq b^{(f_1\zeta-1)}\,m/(Ns^2) \tag{4}$$

$$v = \frac{4(0.4+0.6n_{40})}{mbl+200} \tag{5}$$

$$n_{40} = \left\{\left(\left(\frac{40}{f_1}\right)^2 - 1\right)\left(\frac{b}{l}\right)^4 \frac{(EI)_l}{(EI)_b}\right\}^{0.25} \tag{6}$$

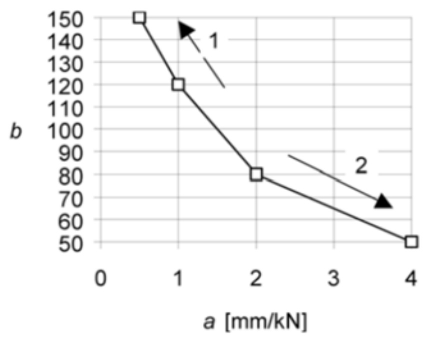

Figure 3 Interaction between the limit values of a, and b; directions 1 and 2 correspond to better and worse behaviour respectively (CEN 208).

Modifications of Hamm et al.

Modifications of the Eurocode 5 method were developed by Hamm et al (2010) in Germany to account for the stricter requirements on vibration performance and for floors with natural frequencies less than 8 Hz. The research, which was based on the assessment of 50 buildings and 100 floors, found timber floors with natural frequencies less than 8 Hz, particularly heavy floors, could have acceptable vibration performance. A light floor on the other hand could perform poorly when subjected to frequencies over 8 Hz. A flow chart that outlines the design procedure is included in Figure 4.

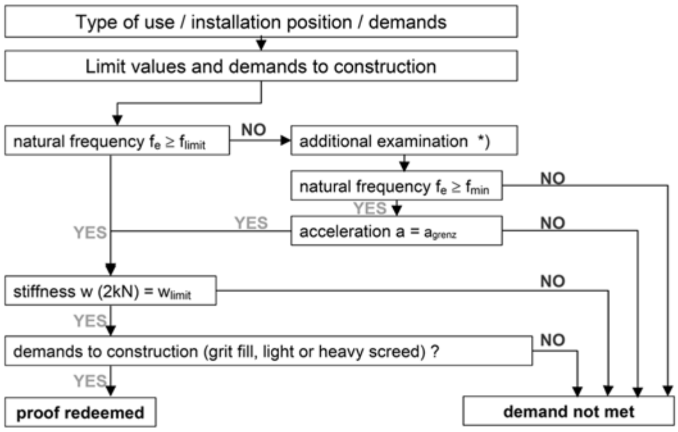

Figure 4 Flow chart for the design and construction of timber floors, the additional examination * only applies for heavy floors with wide spans, or timber concrete composite systems (Hamm et al. 2010).

The frequency is calculated using the same method as Eurocode 5 considering only the static mass of the floor. The stiffness criterion is also calculated using a similar method as the Eurocode, however it is given a more stringent limit value of 0.5 mm and a concentrated load value of 2 kN as opposed to 1 kN. The more stringent criteria were determined by studying the behaviour of a number of floors (Hamm et al. 2010).

If the frequency of the floor is less than 8 Hz, the floor is not necessarily deemed unacceptable, unlike the Eurocode. An additional examination of the acceleration is provided along with the original criteria also being met. The acceleration is calculated using (7 and is limited to 0.05 m/s^2. Where P_0 is the force of one person (taken as 700 N) and the values for the Fourier coefficient α_i and the forcing frequency F_F are given in Table 3. The generalised mass, M_{gen}, is equivalent to half the effective area contributing to vibration performance ((8) where the mass, m, is the self-weight of the floor plus any super-imposed dead load. Values for damping were taken as 1% as outlined by Eurocode 5.

$$\mathrm{a} \approx 0.4 \frac{P_0 \alpha_i(f_1)}{M_{gen}} \frac{1}{\sqrt{\left[\left(\frac{f_1}{f_F}\right)^2 - 1\right]^2 + \left(2D\frac{f_1}{F_F}\right)^2}} \leq 0.05\ m/s^2 \tag{7}$$

$$M_{gen} = m\ \frac{l}{2} b_{eff} \tag{8}$$

Table 3 Fourier coefficient, dependent on the fundamental frequency of the floor (Mohr 1999).

Fundamental Frequency Hz	Fourier coefficient	Forcing frequency F_F Hz
$3.4 < f_l \leq 4.6$	0.2	f_l
$4.6 < f_l \leq 5.1$	0.2	f_l
$5.1 < f_l \leq 6.9$	0.06	f_l
$f_l > 6.9$	0.06	6.9

Mohr Criteria

The International Council for Building Research Studies and Documentation, provides an alternate modification to the Hamm et al. method for frequencies below 8 Hz, and was developed at the Technical University of Munich (Mohr 1999). This method considers a quasi-static floor mass that includes a portion of the live load in the total floor mass (G + 0.3Q) for calculating the natural frequency. Apart from the floor mass being quasi-static, both the frequency and the floor stiffness are calculated by the same method as Eurocode 5. A floor velocity check is included that was derived from the action of a "heel drop" and is given by (9. A damping value of 1% is assigned to floors without any additional boarding's for sound isolation as outlined by Mohr (1999). While in practice a commercial floor will have either a ceiling or an access floor to provide services and sound insulation, a value of 1% for damping is considered in this paper.

$$v_{MOHR} = \frac{0.6}{m_f^{0.5} EI_l^{0.25} EI_t^{0.25}} < v_{lim,MOHR} = 6 \times 100^{(f\zeta-1)} \tag{9}$$

For floors with frequency below 8 Hz the acceleration is calculated using the same methods as outlined by Hamm et al. (2010), however the acceleration limit is less stringent at 0.1 m/s^2.

CLT Handbook

A Canadian research team, FPInnovations, developed a simplified method to specifically assess the vibration performance for CLT floors, which was published in the CLT Handbook (Hu & Gagnon 2011). The criterion ((10) provides an inequality based on the fundamental frequency and the effective stiffness of the floor under a unit load.

$$\frac{f}{\Delta^{0.7}} \geq 13 \tag{10}$$

The deflection is calculated considering a 1-m wide CLT panel and the frequency is calculated considering static mass only. Therefore the deflection can be calculated using (2 and the frequency using (1.

RESULTS AND DISCUSSION

A preliminary design of Floor 1 and Floor 2 was first conducted as a control. Then by varying the cross sectional stiffness, the support stiffness factor (k_m) and the two-way action provided by CLT the floor vibration response was controlled. The results of the effect of these changes on the analytical methods examined in this paper are discussed with the aim to provide an optimised floor design. The optimisation involves minimising the floor panel mass, while ensuring acceptable vibration performance. The results from the analytical methods of Hamm et al., Mohr and the CLT Handbook provided by FPInnovations are included.

Preliminary Design

The preliminary design of Floor 1 and Floor 2 are simply supported, single span CLT panels with elastic moduli of 10.5 GPa (grade F11). Both floors fundamental frequencies were calculated as below 8 Hz, with accelerations above the allowed limits (

Table 4). Therefore they do not satisfy allowable vibrations, with failure due to low natural frequency with larger than acceptable acceleration. However, both floors passed the unit deflection criterion from the methods Hamm et al. and Mohr (with an acceptability of 40-48% and 10-12% respectively). These two methods are actually relatively similar, the difference being Hamm et al. has more stringent acceptability criteria, omits the check on floor velocity and considers static loads only.

Table 4 Results from analytical comparison and study of varying boundary conditions and material stiffness.

		Hamm et al.		Mohr		CLT Handbook	
		Floor 1	Floor 2	Floor 1	Floor 2	Floor 1	Floor 2
Preliminary design. E=10.5 GPa $K_m = \pi^2$ Floor width = 9 m	Frequency (Hz)	5.4	5.19	4.78	4.6	5.4	5.19
	Unit Deflection (mm)	0.12	0.1	0.12	0.1	0.59	0.63
	Limit Deflection (mm)	0.25	0.25	1	1	**0.29**	**0.27**
	Acceleration (m/s^2)	**0.12**	**0.087**	**0.32**	**0.228**	-	-
	Accel. Limit (m/s^2)	0.05	0.05	0.1	0.1	-	-

It can already be observed from the different analytical methods that while they produce similar values for floor frequency and unit deflection, the limit values, are vastly different and therefore will produce vastly different solutions. The accuracy of the values for floor frequency and damping by analytical methods are supported by comparison with experimental and numerical studies from literature. Studies were conducted at the University of New Brunswick that compared experimental analysis with finite element methods for a floor spanning 5.5 m

(Ussher et al. 2014). For a simply supported CLT floor panel, the 1st modal frequency was found to be 11.4 Hz from experimentation and FEM found a close agreement of 11.1 Hz. Using the analytical methods above, considering a dead load of the slab only, the fundamental frequency was calculated as 10.61 Hz. The study also considered the FE analysis of a CLT panel fully fixed at two ends (but did not carry out test methods); it calculated a fundamental frequency of 20.7 Hz, while analytical methods in this paper produce a value of 24.1 Hz.

Trento University also conducted vibration tests on CLT floors, with modal tests producing a fundamental frequency of 13.31 Hz and a damping ratio of 0.95% for a floor spanning 4.2 m and loaded with steel plates to simulate the non-structural load (Casagrande 2014). The analytical result for the floor assuming a floor damping ratio of 1% was 13.38 Hz, therefore both the frequency and the damping ratio were in close agreement with the experimental results.

Increase the Effective Stiffness EI

Increasing the panel's effective stiffness can be achieved by increasing one or both of the Young's Modulus, E, a material property, or the second moment of inertia (I) a geometric property. By increasing either property, a secondary effect of increasing the mass of the cross section will occur. While increasing EI has a positive effect on both the natural frequency and the acceleration of the floor, increasing the mass has only a positive effect on acceleration and a negative effect on frequency.

While it is generally beneficial to increase the EI of a CLT floor panel, it is important to consider the secondary effects of such an increase, both the positives and the negatives. For example, if the panel was constructed from a hardwood F27 grade timber, the elastic modulus would increase to 18.5 GPa and the density to around 850 kg/m^3, increasing the natural frequency and decreasing the acceleration response. The secondary benefits from such a change are the increase in durability, such as decreased need for preservative application and better performance in a moist environment. There is also a positive effect on the shear slip, known as the "rolling shear', of the CLT panel. An experimental study conducted by Hochreiner et al (2014), found that lower grade timber had a rolling shear failure mechanism, whereas failure was by tensile rupture of individual boards for the higher grade specimens, which led to the higher grade specimens having a better post elastic failure behaviour. The trade-offs, however, are larger craning and transportation requirements, due to the hardwood's increased mass, as well as decreased workability, i.e. fixings and cutting requires more energy.

The elastic modulus for the two floors investigated in this study increased until they were deemed acceptable by the respective analytical methods with results included in Table 5. It was found that each method provided vastly different results, with Floor 1 acceptable at 12 GPa according to Mohr and at 17.9 MPa according to Hamm et al. In either case the results show that the vibration floor design would be acceptable using a F27 timber grade.

Table 5 Results from analytical comparison and study of varying boundary conditions and material stiffness.

	Hamm et al		Mohr		CLT Handbook	
	Floor 1	Floor 2	Floor 1	Floor 2	Floor 1	Floor 2
Minimum E (GPa)	17.9	19.2	12.0	13.0	16.2	17.3
Frequency (Hz)	7.06	7.02	5.11	5.12	7.06	6.66

Increase Support Stiffness

The support stiffness factor (k_m) is dependent on the fixity of the end span connection. For the analytical methods considered in this paper the support stiffness is idealised as either pinned ($k_m = \pi^2$), or fully fixed ($k_m = 22.4$) (Smith et al 2007). The unit load displacement can also be adapted to account for full fixity, however since the displacement is already within acceptable limits for the simply supported case, the improved behaviour of fully fixed support was not considered. In reality, the floor is unlikely to be either pinned or fully fixed but somewhere in between. By considering the partially fixed properties of a CLT floor panel support connection, the fundamental frequency can be increased without adding more mass to the system.

An experimental study was conducted at the University of New Brunswick into the effect of end support on the vibration performance of CLT floors. It was found that by increasing the number of screws at the support there was a significant effect on the rotational stiffness of the connection (Maldonado & Chui 2014). The study considered a CLT panel 1 m wide, with spans varying between 2.9 m – 4.5 m and a number of vertical screwed connections (between 1-13) over the 1 m cross section.

The variations in the natural frequency due to the number of screws used for the connection are compared with the Eurocode 5 method for calculating frequency in Figure 5. There are two important observations from the results; firstly that partial fixity causes a significant increase to the natural frequency, approximately 30% for each span tested, and secondly that an increasing span leads to a decrease in differential change, meaning that with increased span there is less effect due to the end support condition[1].

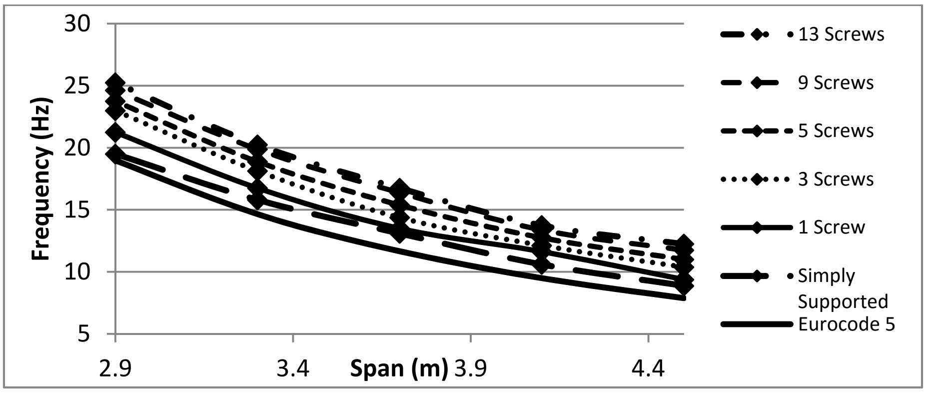

Figure 5 The effect of increasing the number of screw connections on the natural frequency of a CLT floor (Maldonado & Chui 2014). A prediction from Eurocode 5 is included to compare with the test data from the University of New Brunswick.

The results listed in Table 6 show that the analytical methods provide a 5.8% increase in rigidity to satisfy Mohr's criterion whereas a 24.2 % was required by Hamm et al. and 53.7% by the CLT Handbook. The results indicate that partial fixity of supports is a practical option to achieve acceptable levels of vibration with no increase to the modal mass. Results also show that Floor 2 with a lower longitudinal EI requires more fixity to satisfy design limits and therefore this method would be more beneficial for improving the properties of Floor 1.

Table 6 Results from analytical comparison and study of varying boundary conditions and material stiffness.

	Hamm et al.		Mohr		CLT Handbook	
	Floor 1	Floor 2	Floor 1	Floor 2	Floor 1	Floor 2
k_m	12.9	13.4	10.6	11	16.6	17.9
% Fixity	24.20	28.20	5.80	9.02	53.70	64.10
Frequency (Hz)	7.06	7.04	5.13	5.13	9.09	9.41

Two-way action

The final method for increasing the vibration performance of CLT is to consider the two-way action of the material. Timber has traditionally been used as a linear element, whereas the orientation of the boards of CLT renders it with stiffness in both the longitudinal and the transverse direction (Figure 1).

A method of calculating the plate frequency specifically for CLT ((11) and accounting for two-way action has been provided by Thiel (2013). The method considers the effect of a CLT plate supported on 4 sides and requires the value for the longitudinal and the transverse stiffness as well as the twisting stiffness, D^*_{xy}, of the plate.

$$f_{plate} = f_{beam}\sqrt{1 + \frac{2D^*_{xy}}{EI_l}\frac{l^2}{b^2} + \frac{EI_t}{EI_l}\frac{l^4}{b^4}} \tag{11}$$

A method to calculate the twisting stiffness of a CLT plate, is provided in (12 (Silly 2010). This calculation includes a reduction factor, $\kappa_{CLT,P}$, for CLT plates which do not have adhesive between their narrow faces. Since narrow face adhesion is not commonly used in practice the reduction factor is included ((13) where a is the width

[1] Note however, that the study assumed the floor panels were to be supported on CLT walls. For future studies, the effect of supporting the floors on timber LVL or Glulam frames on the vibration performance should be examined.

of the board, t is the thickness of the board and p, q are parameters based on a numerical study and listed in Table 7.

$$D_{xy}^{*} = \kappa_{CLT,P} G_{xy} \frac{t_{CLT}^{3}}{12} \tag{12}$$

$$\kappa_{CLT,P} = \frac{1}{1 + 6p\left(\frac{t}{a}\right)^{q}\left(\frac{t}{a}\right)^{2}} \tag{13}$$

Table 7 Parameters p and q for 3-, 5-, and 7-layer CLT element.

Parameter	3-layer	5-layer	7-layer
p	0.89	0.67	0.55
q	-0.67	-0.74	-0.77

By reducing the width (b) of the original grid layout (9 x 9 m) and accounting for the two-way action of the CLT plates the design limits for each of the analytical methods were satisfied. Table 8 shows that the width of the CLT Floor 1 was reduced from 9 to 3.3 m to satisfy the methods provided by Hamm et al. and from 9 to 7.6 m for Mohr/Richter. The reduction was even more pronounced for the methods by the CLT Handbook, with new floor widths of 2.0 – 2.1 m. The results show that the required reduction in floor width between Floor 1 and Floor 2 are not vastly different. The results from the method by Hamm et al. for example, show a reduction in width of 9 m to 3.3 m for both floors. This indicates that the larger transverse stiffness of Floor 2 is more beneficial for considering the two-way behaviour of CLT rather than the effect of support stiffness or effective stiffness.

The amount of moment transfer between panels is currently unknown. Experimentation on CLT panel-to-panel connections is required to determine the accuracy of these results by calculating the amount of moment transfer between panels.

Table 8 Results from analytical comparison and study of varying boundary conditions and material stiffness.

	Hamm et al.		Mohr		CLT Handbook	
	Floor 1	Floor 2	Floor 1	Floor 2	Floor 1	Floor 2
Floor Grid width (m)	3.3	3.3	7.6	6.4	2.1	2.0
Freq. Increase Factor	1.32	1.37	1.07	1.11	1.68	1.83
Frequency (Hz)	7.13	7.09	5.10	5.10	9.09	9.52

CONCLUSIONS

Analytical methods for calculating the vibration performance of long span cross laminated timber (CLT) floor panels have been compared. The floor panels were considered part of a 9 x 9 m column grid under commercial building loads. Current analytical methods were investigated and compared with finite element analysis and experimental results. The comparison indicated that for single span simply supported beams, there is a general agreement of floor behaviour (natural frequency, velocity and deflection), however, the large difference between limiting values of the analytical methods resulted in vastly different designs.

The methods that were investigated included vibration design calculations from Eurocode 5 and modifications that have been provided by Hamm et al. (2010) and Mohr (1999). The method specifically developed for CLT floors from the CLT Handbook by FPInnovations (2011) was also compared. The modifications provided by Hamm et al. and Mohr provided a method for designing floors with low natural frequencies, between 5-8 Hz, by providing an extra criterion that assesses the floor acceleration. The limit values provided by Hamm et al. resulted in a more conservative floor design than the limit values provided by Mohr. The methods provided by the CLT Handbook generally resulted in the most conservative design.

Floor parameters including the material stiffness, support conditions and two-way plate behaviour were varied to understand the effect on the vibration design. The material stiffness was increased by changing the timber strength grade from F11 up to a F27. The change in material stiffness provided floor designs that satisfied vibration performance. The results indicated that by increasing partial rigidity at the support connections and exploiting the two-way behaviour of CLT plates the floor vibration performance increased to acceptable levels without increasing floor mass.

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